Contrasting FAA and USAF Damage Tolerance Requirements

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Overview

- What Requirements?
- Background
  - USAF
  - FAA
- Damage Tolerance Requirements
  - USAF
  - FAA
- Fail-safe
  - USAF
  - FAA

What Requirements?

USAF

MIL-A-83444, *Airplane Damage Tolerance Requirements*, July 2, 1974

FAA

§ 25.571 Damage-tolerance and fatigue evaluation of structure

(a) General

(b) Damage-tolerance evaluation

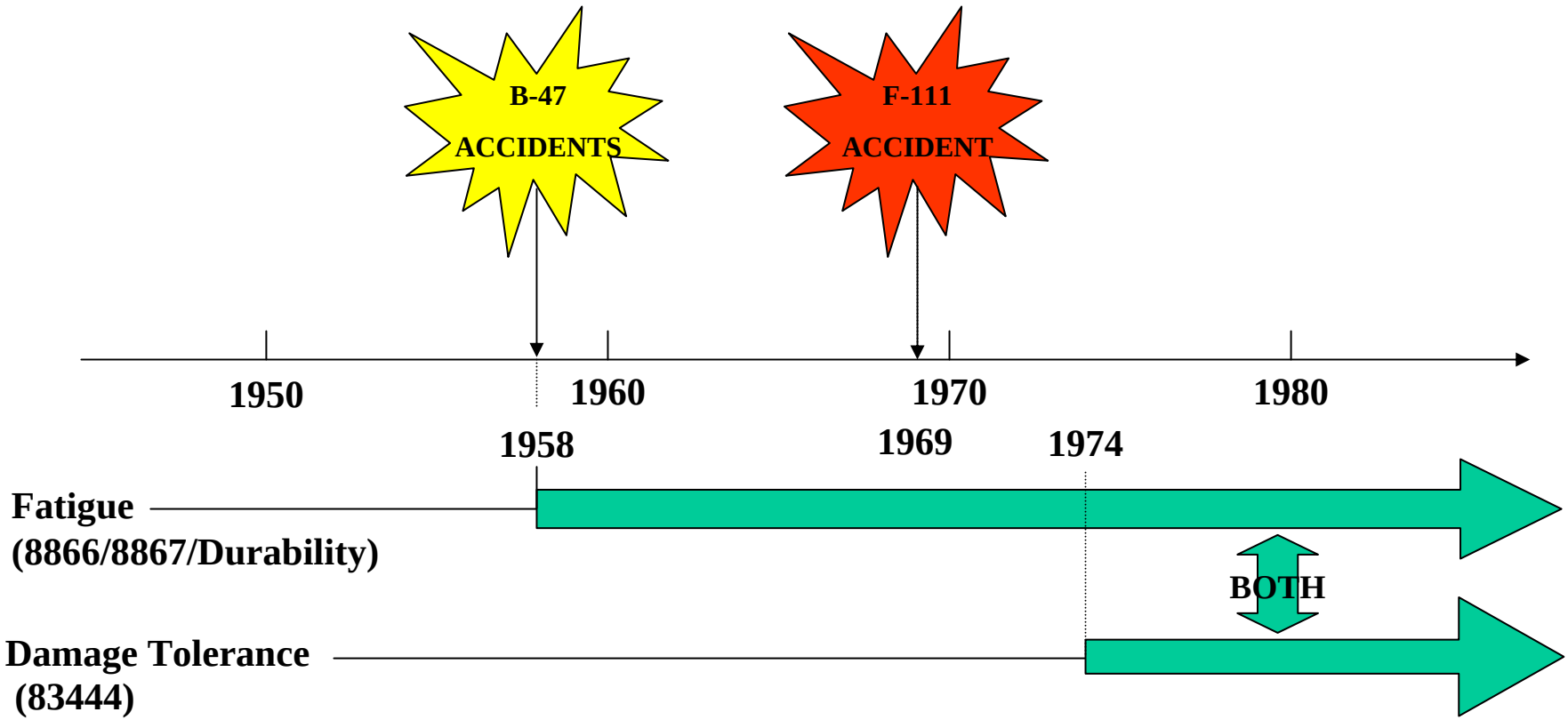
~~(c) Fatigue (safe-life) evaluation~~

~~(d) Sonic Fatigue Strength~~

~~(e) Damage-Tolerance (discrete source) evaluation~~

[Amdt. 25-45, 43 FR 46242, Oct. 5, 1978]

USAF Experience



B-47 Accidents

(1958)

- First flight on December 17, 1947
- Static strength demonstrated with full scale static test and flight loads surveys
- No fatigue life requirement but planned to remain in service until 1965
- Multiple accidents occurred in 1958 which crippled Strategic Air Command
- Majority of failures attributed to fatigue in wing and fuselage fatigue sensitive areas

Aircraft Structural Integrity Program

- Formalized in June 12, 1958
- Primary objectives:
  - Control structural fatigue in operational aircraft fleet
  - Devise methods of accurately predicting aircraft service life
  - Provide the required design process and test techniques that would avoid structural and sonic failures in operational aircraft
- Fatigue requirements:
  - Aircraft must be able to withstand the repeated loads expected during its service life
  - Fatigue life validation by full scale testing
  - Allowable service life equal to a fraction of the test life

F-111 Failure

(22 December 1969)

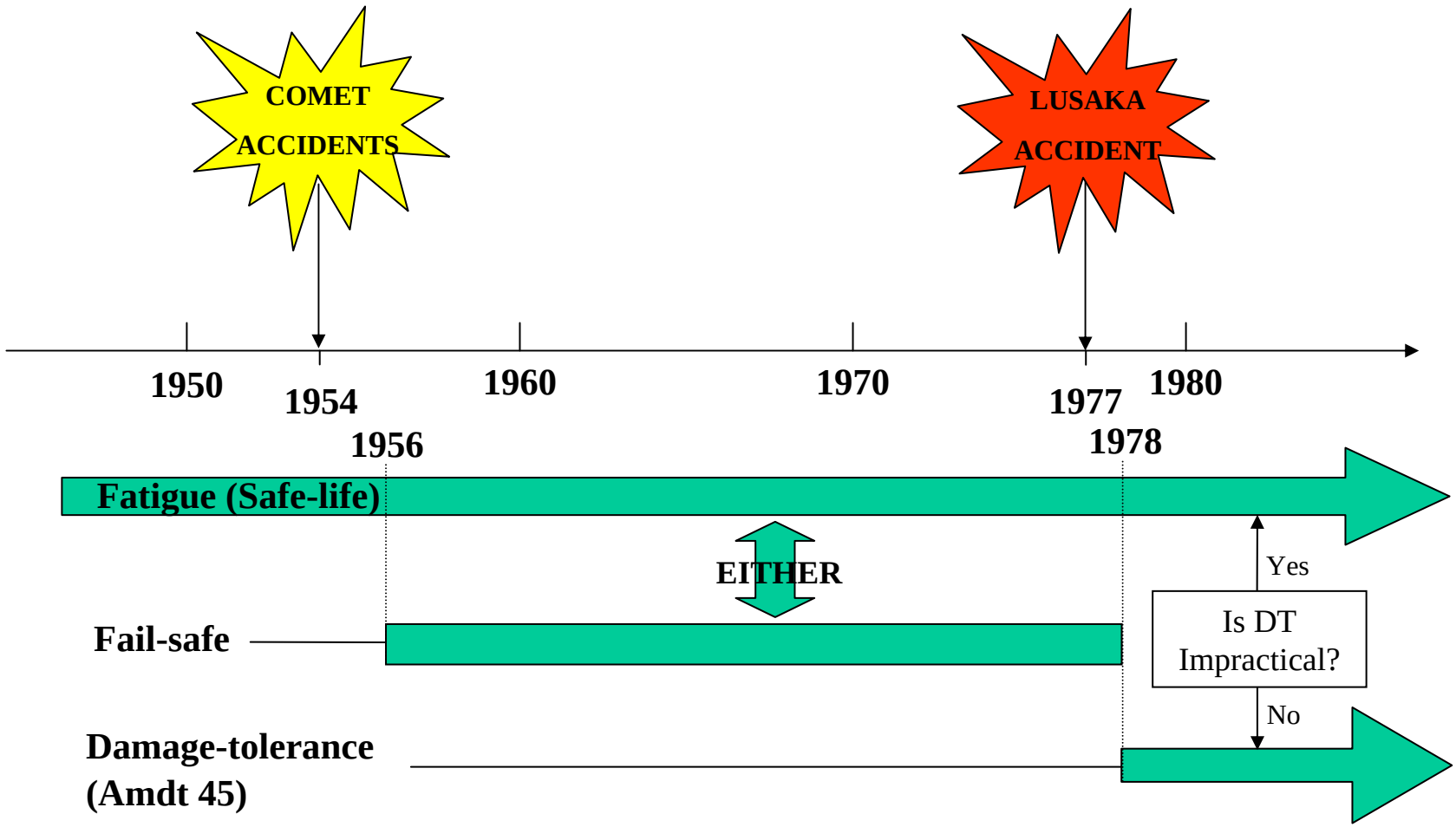
- Safe life design approach used - successfully fatigue tested to 16000 simulated flight hours
- USAF determined 6000 flight hour service life had been demonstrated
- In-flight failure of left wing at 4.0g on aircraft designed for 11g with only 105 total hours
- Examination found large defect in D6ac steel wing structure and small region of crack growth
- “Rogue” defect, small critical damage size, short crack growth life, no fail safe capability

USAF Specification MIL-A-83444

(2 July 1974)

- Specified damage tolerance design requirements for "safety of flight" structure
- "Objective is to protect the safety of flight structure from potentially deleterious effects of material, manufacturing and processing defects…"
- Resulting design should be damage tolerant
  - Crack growth life, assuming presence of "rogue" flaw when structure is new, must exceed minimum specified
  - Inspection intervals not less than specified
  - Minimum level of large damage capability (e.g. two bay crack) required <u>if</u> structure qualified as fail safe

FAA Experience



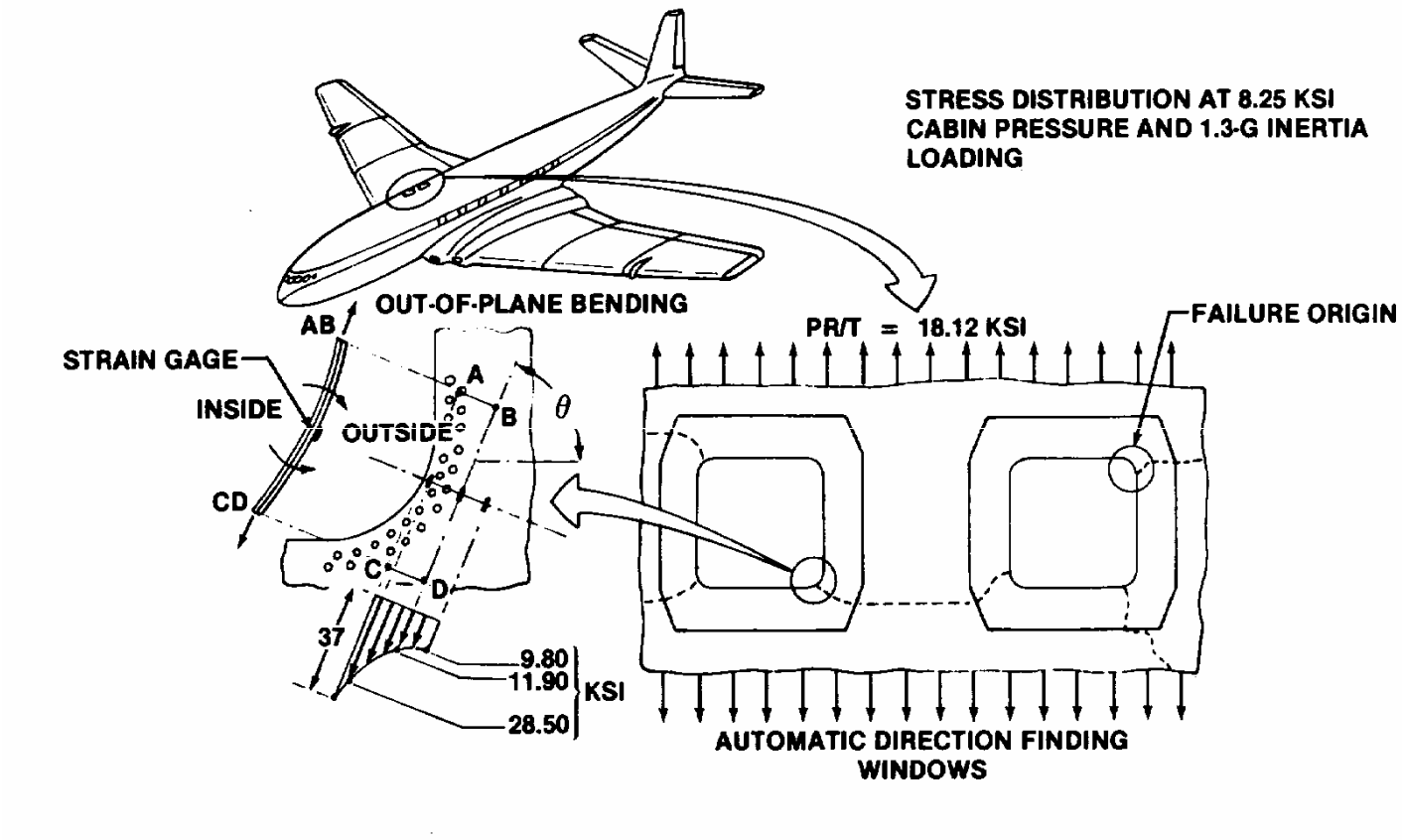
CAR 04.313 Fatigue Strength
(1945)

- Fatigue recognized as a threat to structural integrity
- Required designing, “in so far as practical, to avoid points of stress concentration where variable stresses above the fatigue limit are likely to occur in normal service”

Comet Failures
(1954)

- Two apparent catastrophic cabin ruptures at altitude
  - 1/10/54 - G-ALYP, @30,000ft., 3680 hrs, 1286 cycles
  - 4/8/54 - G-ALYY, @35,000ft., 2702 hrs, 903 cycles
- Cabin failure during testing on G-ALYU in summer of 1954 with 1230 operational cycles + 1830 test cycles = 3060 cycles
- Examination of G-ALYU & G-ALYP showed evidence of fatigue at corner of passenger window and automatic direction finding windows
- Premature fatigue, small critical damage size and no crack arrest capability

Comet G-ALYP Failure



Ref. Damage Tolerance in Pressurized Fuselages, 11th Plantema Memorial Lecture, 14th ICAF, June 10-12, 1987

Impact of Comet Failures

- Increased concern with respect to pressurized fuselage design
  - Allowable 1P stress levels
  - Detail design features
  - Crack arrest capability
- Increased respect for fatigue threat
- Highlighted value of full scale fatigue testing
- Increased merit of fail-safe philosophy

CAR 4b.270 Fatigue Evaluation
(1956)

- Required evaluation of structure which is critical for fatigue
- Introduced concept of “Principal Structure Elements”
- Adopted “Fail Safe” as an option to “Safe Life”.

B707 Lusaka Incident

(14 May 1977)

- Separation of right horizontal stabilizer & elevator lead to loss of aircraft and crew
- Undetected fatigue cracking in rear spar upper cap rendered a fail safe certified design unsafe
- Same cracking, though less severe, found on other aircraft after incident
- Final straw in raising awareness of fatigue threat in aging aircraft which were originally certified and now “managed” as fail safe

FAR 25.571, Amendment 25-45

(5 October 1978)

- Applicable to new designs
- Complete revision to FAR 25.571
- Title change to “Damage-tolerance and fatigue evaluation of structure”
- Recognized accidental damage (AD), and environmental damage (ED) as additional threat to structural integrity
- Required a damage tolerance evaluation unless impractical

FAR 25.571, Amendment 25-45

(cont'd)

- Retained the fatigue evaluation "option" for those areas where a damage tolerance evaluation is impractical
- Required establishment of "inspections or other procedures" based on results of the evaluations and inclusion in the maintenance manual required by 25.1529
- Required a "damage tolerance (discrete source) evaluation" for
  - 4 lb bird strike up to 8000 ft
  - Propeller or uncontained fan blade
  - Uncontained engine failure
  - Uncontained high energy rotating machinery failure

“Damage Tolerance” Rule

- Two different fatigue threat mitigation approaches given as options:
  - Damage tolerance (DT) based inspection program
  - Life Limits
- DT “option” required unless it can be show to be impractical
  - AC 25.571-1C advises that DT approach is only considered impractical for landing gear

DT Option

- DT evaluation must be performed (analysis/test) and DT characteristics quantified
  - Crack growth (a versus N) based on applicant defined operational loading
  - Critical damage size (a_{CRIT}) based on rule specified static load conditions
- Inspection method, threshold (start point) and interval must be established and be consistent with the structure's DT characteristics

DT Option (cont'd)

- DT characteristics are not specified (e.g. there is **no** "2 bay" crack requirement or minimum acceptable safe crack growth life)
- Inspection program details are not specified (e.g. there is no minimum threshold point or interval)
- BOTTOM LINE: Inspections established must preclude catastrophic failures in light of quantified DT characteristics

Comparison of “Watershed” Events

	F-111	Lusaka
Date	December 22, 1969	May 14, 1977
Airplane Model	F-111	B707-300
Fatigue Design Basis	Safe-life	CAR 4.270 Fail-safe
Fatigue Test	Yes – 16,000 Hours	No
Design Life (DL)	6,000 Hours	20,000 Flights/60,000 Hours
Component Involved	Left Wing Pivot Fitting Lower Plate	Right Horizontal Stabilizer Aft Spar Upper Chord
Material Involved	D6ac Steel (220-240 KSI)	7079-T6 Aluminum
Total Time in Service at Failure	105 Hours	16723 Flights/47621 Hours
Fraction of DL at Failure	.071	.8
Category of Fatigue	Anomalous	Unexpected normal

Outcome of USAF & FAA Experiences

	CONCLUSIONS	OBJECTIVE	STRATEGY
USAF	• Safe-life approach does not preclude selection of unforgiving materials, design concepts and working stress levels. • Safe-life does not adequately address potential defects.	• A design that has a minimum level of tolerance to defects.	• Create supplemental design requirements that specify minimum crack growth life and residual strength attributes that a structure must possess with specified cracks assumed to be present as manufactured.
FAA	• Fail-safe approach does not adequately ensure that fielded designs fail safely. • Fail-safe approach addresses residual strength but neglects inspectability.	• Effective inspections that can be relied on to ensure safety.	• Create a new fatigue rule that requires quantification of crack growth and residual strength characteristics. • Require correlation between characteristics and any inspections established. • Provide an alternative if inspections are impractical.

USAF vs. FAA DT Requirements

	USAF	FAA
Primary motivation for:	Safe-life approach inadequate	Fail-safe approach inadequate
Applicability:	New airplane designs – safety of flight structure	New airplane designs – safety of flight structure
Objective:	Safety during design service	Safety indefinitely
Outcome:	Design attributes (& in-service inspections as required)	Maintenance Actions*
Incorporation Philosophy:	Replace safe-life	Replace fail-safe
Threats addressed:		
Normal fatigue	No (Addressed by Durability Requirements)	Yes
Anomalous fatigue	Yes	Yes
Unexpected normal fatigue	No	No
Provision for alternative approach if damage tolerance impractical?	No	Yes

**** In-service inspections expected.***

Design Attributes vs. Maintenance Actions

"This specification contains the damage tolerance design requirements applicable to airplane safety of flight structure. The objective is to protect the safety of flight structure from potentially deleterious effects of material, manufacturing and processing defects through proper material selection and control, control of stress levels, use of fracture resistant design concepts, manufacturing and process controls and the use of careful inspection procedures."

Scope paragraph of MIL-A-83444

"The purpose of the proposal was to establish an evaluation requirement rather than an absolute requirement for the strength, detail design, and fabrication of the structure".

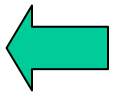
Response to comments in Preamble to Final Rule, October 5, 1978

"Based on the evaluations required by this section, inspections or other procedures must be established, as necessary, to prevent catastrophic failure……"

§ 25.571 (a)(3)

USAF vs. FAA DT Prescribed Requirements

	USAF	FAA
Design Concept: (i.e. single or multiple load path)	No	No
Initial crack sizes:	Yes	No
In-service detectable crack sizes:	Yes	No
Cracking scenarios:	Yes	No
Minimum crack growth life:	Yes	No
Inspection intervals:	Yes	No
Residual strength:	Yes	Yes



Design Concept

"It should be emphasized that while the "Fail Safe" concept appears to offer a larger degree of safety, it is the intent of the new criteria that structure qualified to either category have equal safety".

Wood, H.W., Application of Fracture Mechanics to Aircraft Structural Safety, Engineering Fracture Mechanics, Vol. 7, 1975.

"… the applicant would be allowed to apply the damage-tolerance approach to both single load path and multiple load path structure. The FAA believes the applicant can, by sufficient analysis and testing, establish that a single load path structure has sufficiently slow crack growth properties so that, if a crack were to develop, it would be discovered during a properly designed inspection program."

Preamble to Amendment 45 Notice of Proposed Rulemaking, August 15, 1977

Fail-safe

- Removed from § 25.571 with Amendment 45.
- Integrated into the USAF requirements as an optional design concept that, if chosen, must possess specified attributes based on inspectability.
- Past FAA and current USAF brands of “fail-safe” share similarities at the conceptual level but differ significantly at the detail level.

USAF vs. FAA Fail-safe

	USAF	**FAA Pre-Amd 45**
Included as Optional Approach:	Yes	Yes
Associated with Multiple Load Path Structure:	Yes	Yes
Outcome:	Design Attributes*	Design Attributes

**** Plus inspections as required***

FAA Pre-Amd 45 Fail-safe

"It must be shown by analysis, test, or both, that catastrophic failure or excessive structural deformation, that could adversely affect the flight characteristics of the airplane, are not probable after fatigue failure or obvious partial failure of a single principal structural element. After these types of failure of a single principal structural element, the remaining structure must be able to withstand static loads corresponding to the following:……"

FAA Pre-Amd 45 Fail-safe Application

"Generally, manufacturers satisfying the requirements under the fail-safe concept merely substantiated the structures for failure of single principal elements under static loading conditions. Although it was recognized that inspections were necessary there were no specific requirements to determine safe inspection periods based on crack growth or remaining life of secondary structure in the event the primary member failure was not immediately obvious."

Swift, T., Verification of Methods for Damage Tolerance Evaluation of Aircraft Structures to FAA Requirements, Proceedings of the 12th Symposium of the International Committee on Aeronautical Fatigue, Toulouse, France, 1983.

Certified Fail-Safe Capability for Fuselage Structure in Longitudinal Direction

Airplane Model	"Fatigue failure or obvious partial failure of a single principal structural element"	Skin Crack size
DC-10[1]	2 Frame bay skin crack with central crack stopper failed but frame intact.	40"
DC-9	1 Frame bay skin crack.	20"
B737	1 Frame bay skin crack.	20"
B727	1 Frame bay skin crack.	20"
B747	12" Skin crack.	12"
L1011[2]	1 Crack stopper bay skin crack with center frame failed.	20"

1. Crack stoppers located under frames.
2. Crack stoppers located between frames.

USAF vs. FAA Fail-safe Prescribed Requirements

	USAF	**FAA Pre-Amd 45**
Initial crack size for intact structure.	Yes	No
Damage size after stable load path failure or crack arrest.	Only for “fail-safe crack arrest” structure	No
In-service detectable crack sizes.	Yes	No
Cracking scenarios before and after stable load path failure or crack arrest.	Yes	No
Minimum crack growth life before and after stable load path failure or crack arrest.	Yes	No
Inspectability of stable load path failure or crack arrest.	Determined by manufacturer	Obvious during normal maintenance.
Residual strength.	Yes	Yes

CLOSURE

- USAF DT ≠ FAA DT
- USAF Fail-safe ≠ FAA Fail-safe
- FAA Fail-safe was removed in 1978.